OHIO UNIVERSITY
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Frequency Spectrum for New Aviation Data Links: Initial Study Results

ICNS

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Outline

- Overall Study Aim:
  - Identify key factors involved in the use of alternate spectrum in various bands for a future integrated CNS data link
- Background
- Overview of current related efforts
- Key factors in spectrum selection
- Desired new ADL system attributes
- Example spectral regions
- Summary

Spectrum Shortage or Not?

IEEE *Spectrum* "Bonanza" (2)

SOURCES OF NEW SPECTRUM

ASSIGNED SERVICE[1]	FREQUENCY BAND	USABLE MHZ
Mobile Communications		
Terrestrial (3-G advanced wireless service)	1.7–2.1 GHz 698–794 MHz (UHF band)	120 84
MVDDS/ITFS (flexible use)[2]	2.5–2.7 GHz	132
Satellite (MSS)	1.6–2.0 GHz	98
Video/Broadband Internet		
Terrestrial MVDDS	12.2–12.7 GHz	500
Broadcast digital television (DTV)[3]	54–72 MHz, 76–88 MHz, 174–216 MHz, 470–698 MHz (VHF band)	294
Satellite (fixed service)	17.2–20.2 GHz, 27.5–30.0 GHz (Ka band)	5500
Direct broadcast satellite (DBS)[4]	12.2–12.7 GHz	240
Miscellaneous		
Unlicensed National Information Infrastructure (NII)	5.5–5.7 GHz (proposed)	255
New broadband wireless services, satellite, and terrestrial (V band) (flexible use)	38.6–40.0 GHz, 47.2–48.2 GHz	5600
Millimeter wave bands (broadband video/data)	71–76 GHz, 81–86 GHz, 92–95 GHz (proposed)	13 000

[1] Flexible use may permit other services in same bands.

[2] New mobile communications spectrum in multichannel multipoint data service/instructional television fixed service (MMDS/ITFS) bands based on a 2002 plan proposed by a major user coalition.

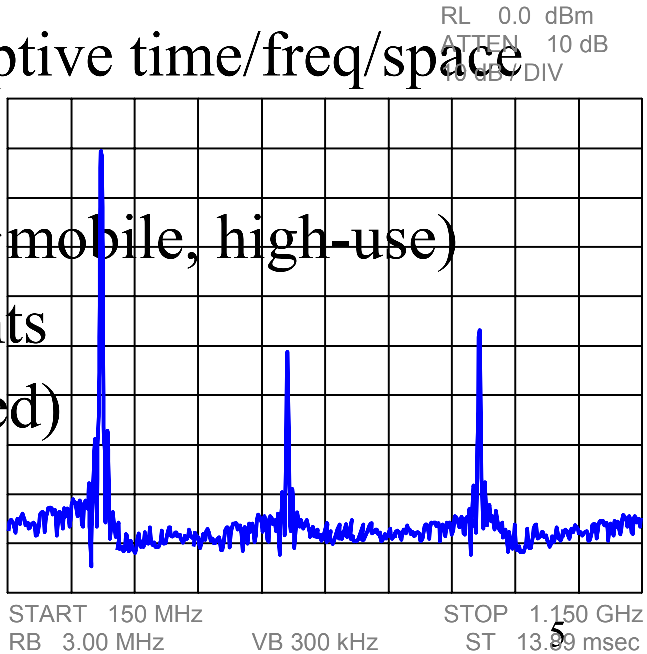
[3] Relocation of analog TV service to new 6-MHz digital TV channels in VHF band will provide incumbent broadcasters the ability to multicast up to five TV channels. The Federal Communications Commission is also considering a new wideband underlay service on guard band (unused) VHF channels. Other underlays have also been proposed in the 900-MHz and 3.6-GHz bands.

[4] New DBS spectrum is primarily available for service to the western United States and includes approximately one hundred 24-MHz "channels," each of which can carry 10 TV program services.

- No *aeronautical* mobile bands listed
- Yet "pressure is on" to "free up" parts of dedicated aeronautical spectrum

IEEE *Spectrum* “Bonanza” (3)

- Key technologies for spectrum “bonanza”
  - Spread spectrum
  - Adaptive antennas
  - “Mesh” networking (relaying)
  - Software Defined Radio (SDR): adaptive time/freq/space
- Key regulatory revisions
  - Re-allocation (incumbent, low-use→mobile, high-use)
  - New use and/or leasing by incumbents
  - Spectral sharing (including unlicensed)



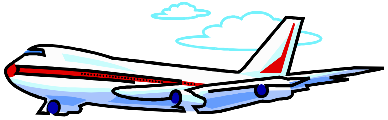
…and from DARPA, NSF

- DARPA's Advanced Technology Office
  - *neXt Generation (XG) Communications* program
  - "All spectrum may be assigned, but
    …most spectrum is unused!"
  - "XG is developing the technology and system concepts for DoD to dynamically access all available spectrum"
- NSF's Computing & Communications Foundation Division
  - *Networking Technology & Systems* (NeTS) program
  - "Explore dynamic spectrum management architectures and techniques"

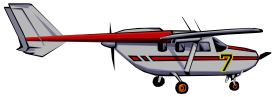
Motivation

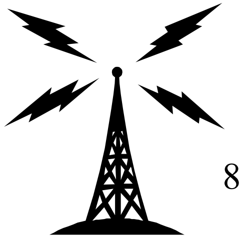
- Need for additional communication capabilities in civilian aviation is well documented
  - FAA's National Airspace System (NAS) "modernization blueprint" [1]
  - Numerous papers from recent professional conferences
    - Digital Avionics Systems Conferences (DASC), e.g., [2], [3]
    - Integrated Communications, Navigation, and Surveillance (ICNS) workshops, e.g., [4], [5]
  - Growth of passenger communications is also expected [6]
- We began with premise that new capabilities are unquestionably in need, for the benefit of the aviation community.

Study Focus



- Key factors in spectrum selection for aviation data links
- Systems that can deliver VDL-or-higher data rates
- Aeronautical spectra (C, N, or S)
- Two or three lowest layers of the communications protocol stack:
  - physical layer (PHY)
  - data link layer (DLL)
  - medium access control (MAC) layer





Potential Spectral Regions

- In principle, Vast amounts of unused spectrum, at frequencies above those in common use
  - e.g., V band ~ 45 GHz
  - Technologies are not presently available to economically deploy communication systems in these bands
- Propagation conditions favor use of lower frequencies for aeronautical transmission ranges of interest
  - Tens of meters to a few hundred kilometers
- Restrict attention to frequency bands below *Ku* band (12 GHz), for A$\rightarrow$G and G$\rightarrow$A communication (higher *f*'s possible for satellites)

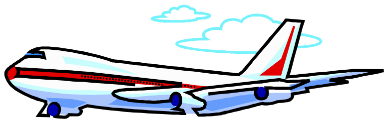
Potential Spectral Regions (2)

- For the lower frequency limit, we selected the upper limit of the HF band (lower limit of VHF band), approximately 30 MHz
  - To support multiple users with data rates ~ 100kbps or more requires more bandwidth than available in HF band and ↓
- Hence, we focus on VHF, UHF, and SHF bands
- Also most likely that any new ADL system will be deployed in spectrum already dedicated to aeronautical applications, either communications or otherwise.

Potential Spectral Regions (3)

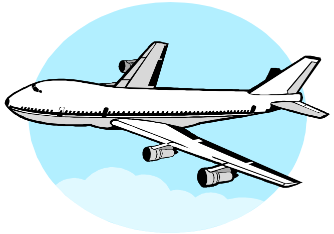
System or Spectrum	Frequency Band	Comments
VDLM3	118-137 MHz	FAA choice for digital voice & data. Data rate limited. Maintaining only 25 kHz channel BW $\Rightarrow$ only moderate data rate achievable.
ILS Glideslope	329-335 MHz	Only $\cong$ 5 MHz spectrum, but good propagation conditions. Coexistence with tone-modulated ILS signal is biggest challenge.
Universal Access Transceiver (UAT)	Two 1 MHz channels: 971 MHz (CONUS), 981 MHz (Alaska)	Developed in FAA Capstone (ADS-B) project. Only two channels currently; design modifications needed for increased data rates. Peer-peer user addressing not currently available.
Military UHF	225-328.6 MHz 335.4-399.9 MHz	Existing transceivers very high power, making coexistence very challenging. Commercial use of military spectrum is likely a large administrative and political challenge.
Microwave Landing System (MLS)	5-5.25 GHz	MLS not deployed widely. Technologies for this band less mature, but *very* wide bandwidth available. Propagation conditions may dictate use of directive antennas, and/or use in shorter range conditions.

Current Related Efforts: NEXCOM (1)



- NEXCOM is **(quote)**
  - "FAA's radio system of the 21st century. …
  - An analog/digital system incorporating latest technological advances in radio communications
  - Will provide capability to
    - accommodate additional sectors and services
    - reduce logistical costs
    - replace expensive to maintain VHF and UHF radios
    - provide data link communications capability
    - reduce A/G RF Interference
    - provide security mechanisms.
  - When completed over 46,000 radios will be installed throughout the FAA system."

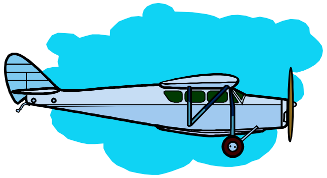
NEXCOM (2)

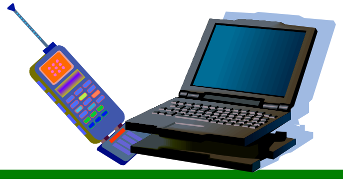


- Operates in dedicated aero spectrum at VHF
- Uses existing FDMA channel structure
- Modes 1-3, plus analog 8.33 kHz AM
- For mode 3 (TDMA)
  - Maximum data rate is 19.2 kbps for ALL 4 time slots
  - Differential 8PSK modulation
  - 3 or 4 time slots
  - Time division duplexing
  - Point-to-point A→G and G→A, plus G→A broadcast

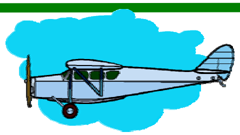
Current Related Efforts: SATS (1)

- Small Aircraft Transportation System (SATS) **(quote)**
  - "… project's initial focus to prove that four new operating capabilities will enable safe and affordable access to virtually any runway in the nation in most weather conditions." [12]
    - on-board computing,
    - advanced flight controls,
    - Highway in the Sky displays,
    - automated air traffic separation and sequencing technologies."
  - Last one relies on efficient and secure CNS

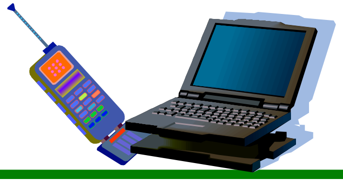




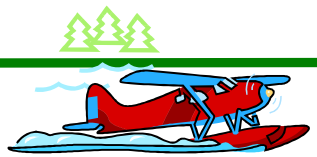
SATS (2)



- Demo done (NASA Glenn) using VDL4
- Next stage planned is transfer of demo system to SATSLab and AIC for experimental evaluations and commercialization.
  - May require <u>substantial</u> changes to demo system in terms of components, capabilities, and modes of operation.
  - Final SATS/AI (even lowest few layers) likely substantially different from demo system, in terms of
    - <u>**frequency band of operation**</u>
    - available data rates and channel bandwidths
    - number of simultaneous users
    - range and spatial discrimination

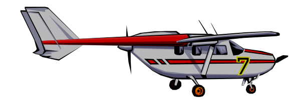


Current Related Efforts: UAT (1)



- Universal Access Transceiver (UAT)
  - Mostly applied to surveillance applications, in particular Automatic Dependent Surveillance—Broadcast (ADS-B).
    - Successfully deployed on a trial basis in Alaska. Plans for its use in contiguous US, and standardization, underway
  - Fairly simple ($\Rightarrow$ robust) binary modulation, to reduce aircraft radio costs
  - Like VDL3, uses time slotting, and burst transmissions
    - Aircraft transmissions not assigned to slots--randomly accessed [14]
  - Current UAT transceivers canNOT provide individual message addressing and true peer-to-peer connectivity

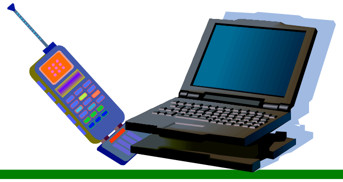
UAT (2)



- Requires a dedicated 1 MHz channel
- Time division duplexing
- Maximum data rate 1004.167 kbps for ALL users (Total) with no packet collisions and no overhead
- Practical throughput ~ 0.36(0.82)1Mbps ≅ 295 kbps for <u>all</u> users (Total); 820 kbps maximum if synchronized (coordinated among all users)
- Point-to-point A→G and G→A, plus G→A broadcast

Current Related Efforts: AIC (1)

- Airborne Internet Consortium
  - Recently formed group [9], also termed the Airborne Internet Collaboration Forum
  - Members from aviation industry, government organizations, academia
- Group purpose
  - Encourage the development of open systems architecture and standards for aviation digital communications
  - Foster and promote internet protocols in aviation
  - Develop intellectual content to guide and influence public and private investment



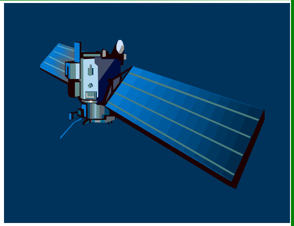
AIC (2)

- Group meetings have sought participation, discussed group's aims, and outlined items for a workplan
- Nascent workplan items of direct relevance to our work:
  - Integrated CNS requirements
  - Architectural candidates, trade-offs and evaluation
  - AI system design
  - Test and evaluation
  - AI design and use of VDL, SAT, 802.11…
  - Applicable technology assessment
  - Applicable communication standards assessments.

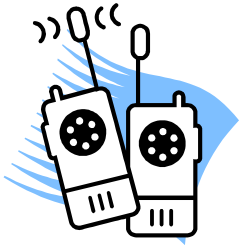
Key Factors in Spectrum Selection

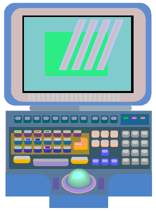
- **Propagation**
  - Best-case, "free-space" path loss is *20log(4πdf/c)* dB, so at a given distance, path loss increases by 20 dB per decade in *f*
    - Example: *d*=10km, *PL*=92 dB at *f*=100MHz, *PL*=112 dB at *f*=1GHz
  - Other attenuations (absorption, scattering, etc.) also generally increase with frequency
  - Conclusion: For a given amount of transmit power, link range is maximized if carrier frequency is minimized

Key Factors in Spectrum Selection



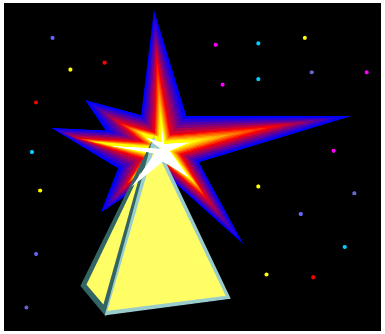
- **Technology**
  - Desire hardware/software, systems, subsystems that are "readily available," or "nearly available"
  - Re-use of existing techniques, software, hardware is economically attractive, and can optimize reliability
  - Examples:
    - Wireless LAN technologies developed for use in the ISM bands (2.4 GHz, 5.8 GHz)
    - Cellular technologies (800-900 MHz bands)



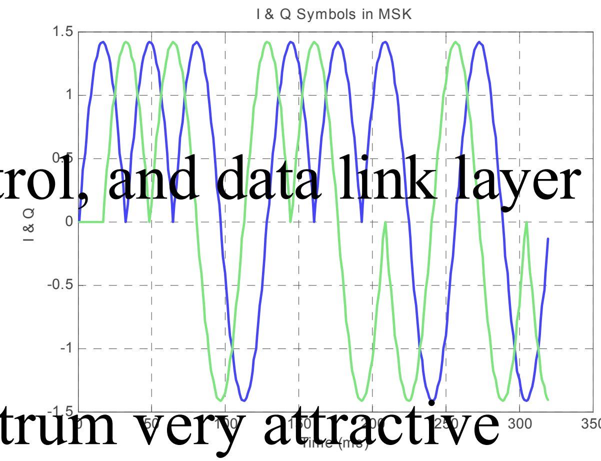


Key Factors in Spectrum Selection

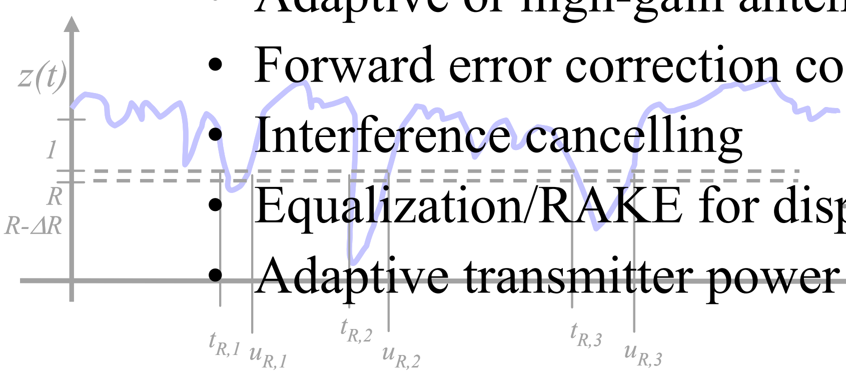
- **Spectrum "Availability"**
  - CAN we (are we permitted to) use a given spectral region for aeronautical applications?
    - Regulatory constraints
    - Existing users of the band, and existing systems
  - New ADL most easily deployed in systems already designated (reserved) for aeronautical use

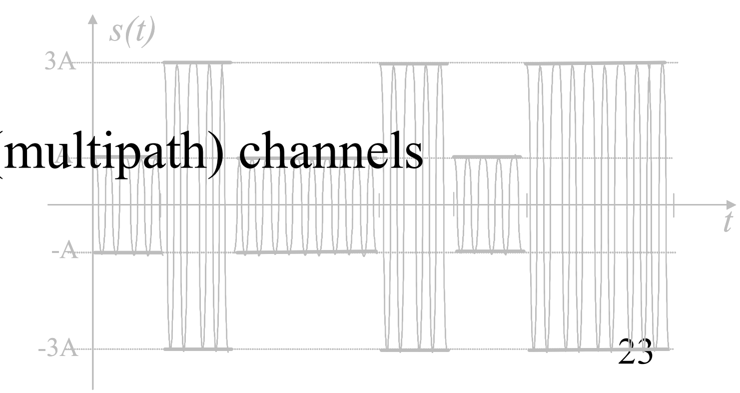


Key Factors in Spectrum Selection



- **Waveforms**
  - Which physical, medium access control, and data link layer techniques are best suited?
  - For multiple access: FD? TD? CD?
  - For robustness, security, spread spectrum very attractive
  - Advanced processing can be used to enhance performance
    - Adaptive or high-gain antennas (easiest at higher frequencies)
    - Forward error correction coding
    - Interference cancelling
    - Equalization/RAKE for dispersive (multipath) channels
    - Adaptive transmitter power control





Desired ADL Attributes

- For widespread acceptance, ADL system must offer capabilities not present or not fully supported by existing systems.

- Generally $\Rightarrow$ New ADL system
  - Should offer higher R_b than existing systems
  - Should be able to serve large # users “simultaneously” in any given geographic area
  - Geographic area (range for air-ground, ground-air, or air-air communications) should be as large as possible
  - Connectivity should be ideally peer-to-peer

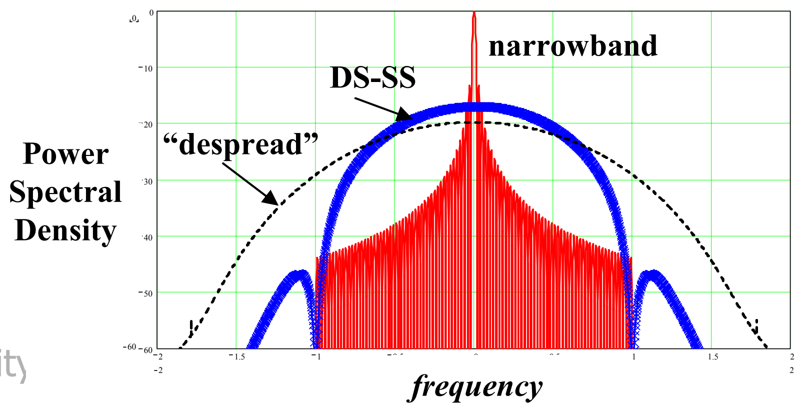
Desired ADL Attributes (2)

- Allow wide variety of data rates & data traffic types, with differing requirements on QoS (latency, integrity)
  - Variety of message rates would enable ADL system use for multiple purposes, enhancing acceptance.
- Last, system should be reliable $\Rightarrow$ redundancy, and should be secure in several ways
  - Difficult to spoof
  - Difficult to eavesdrop upon, for privacy reasons
  - Difficult to disrupt or overload
- Finally: standardization essential

Note on Spread Spectrum

- Use of spread spectrum noted for security advantages
- Spread spectrum also of interest for
  - Robustness (to multipath, interference…)
  - Popularity
    - All new cellular systems are spread spectrum
    - Wireless LANs are spread spectrum
    - All secure military systems use spread spectrum
    - EUROCONTROL experimenting with spread spectrum

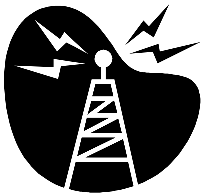
- This has focused some of our work on analysis & simulation of performance of SS



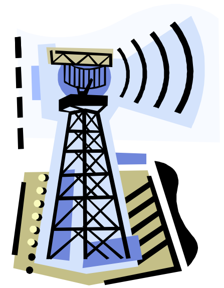
“Macro” Diversity

- Use of different frequency bands simultaneously, to improve performance, availability, and data rate
  - Adaptively utilize all time/frequency/spatial dimensions
- Two limited versions
  - Adaptive “band hopping”
    - Select whatever band is available, as needed
  - Scheduled “band hopping”
    - Example: use VHF band for long range, lower data rate messages during en-route transmissions, then SHF band for short-range, higher data rate messages in terminal/surface areas

Example Spectral Regions (1)



- ILS Glideslope band (~329-334 MHz)
  - Good propagation conditions
  - Moderate bandwidth
  - Coexistence with ILS needs further study
    - Orthogonal allocations
    - DS-SS spectral overlay
  - Mostly available technology at RF
- VHF band (current 118-137 MHz)
  - Good propagation conditions
  - Moderate-to-large bandwidth
  - Coexistence with AM, VDL big issue, i.e., supplant VDL?
  - Mostly available technology at RF



Example Spectral Regions (2)

- “UAT band”
  - Acceptable propagation conditions
  - Moderate bandwidth *IF* the channels can be obtained
  - Coexistence with UAT and JTIDS
    - Orthogonal allocations
  - Mostly available technology at RF
- Military UHF

  - Similar to UAT
    - Acceptable propagation conditions
    - Moderate bandwidth *IF* the channels can be obtained
    - Coexistence with existing systems
    - Mostly available technology at RF
  - Biggest issue: civilian use of military spectrum

Example Spectral Regions (3)

- MLS
  - Short-range propagation conditions (unless high-*G* antennas)
  - VERY large bandwidths $\Rightarrow$ high data rates, large # users
  - Coexistence with MLS signals
    - Orthogonal allocations
    - DS-SS spectral overlay
  - Mostly new (and lower transmit power) technology at RF
  - Added motivation: since spectrum being "coveted" by other (non-aeronautical) entities, USE it or LOSE it!

Summary

- We considered a number of potential spectral bands for use in a new aviation data link system
  - Required that we also consider a number of existing aeronautical systems
- One obvious conclusion (not new!)
  - Existing aeronautical spectrum inadequate to satisfy currently-projected communications demand for the future, using existing systems.
- Clear need for development of a new ADL system to provide SATS, Airborne Internet, and/or other CNS services

Summary (2)

- New services would operate *in conjunction with* existing services, *not* as replacement for all existing services, particularly during transition(s).
- For moderate data rates and good range, ILS-GS band could be suitable for a new ADL system
- For airport surface and terminal airspaces, MLS band, with its capability for large data rates, is most attractive

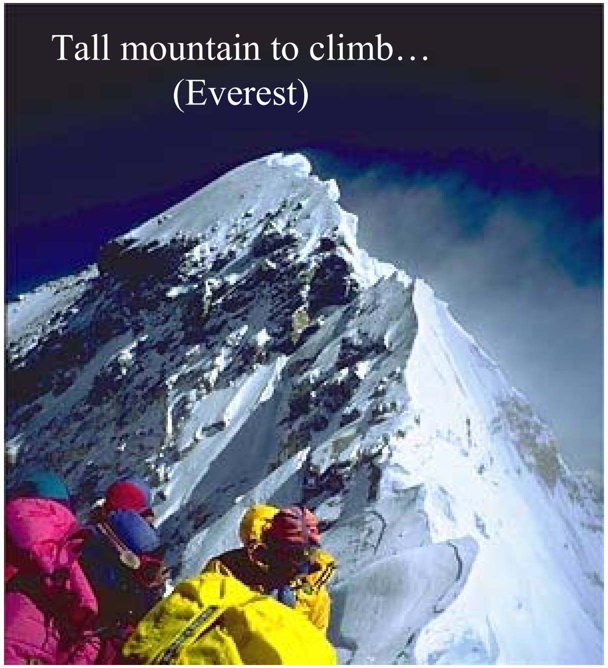
Future Work

- Extend analyses, simulations for ILS-GS and MLS
  - Better channel models, spatial variation, etc.
- Waveform and MA design for MLS
  - Prototyping and testing for surface/terminal communications and to maintain aeronautical spectral rights
- Cooperation with radio manufacturers, Airborne Internet Collaboration Group, NASA, FAA, etc.
- Determination of feasibility of using military UHF spectrum
- Multi-band analyses

Questions?

Backup Slides

- General list of info used as inputs
- Specific system info used as inputs
- Some ILS-GS and MLS technical results



Task Review: Task 1, Study Inputs

- Spectrum Availability: comprehensively, consider
  - Users of the band
  - Geographic regions for systems? Spatial re-use rules?
  - General concept of operations for each system
  - Communication link & waveform parameters
    - Transmit power, minimum acceptable received power, & signal quality requirements (*SNR, SIR,* P_b, etc.)⇒typical/maximum ranges
    - Spatial discrimination (i.e., antenna directivity)
    - Typical link budget propagation models used for system planning
    - Modulation, FEC coding, Multiplexing, Multiple access
  - Spectral characteristics
    - Required spectral mask for each band
    - CCI, ACI and requirements on spurious emissions
- Likely will NOT obtain all this info for any system!

Task Review: Task 1 Inputs (2)

Table 2. Existing System Parameter & Feature List for Four AI Candidate Spectral Regions.

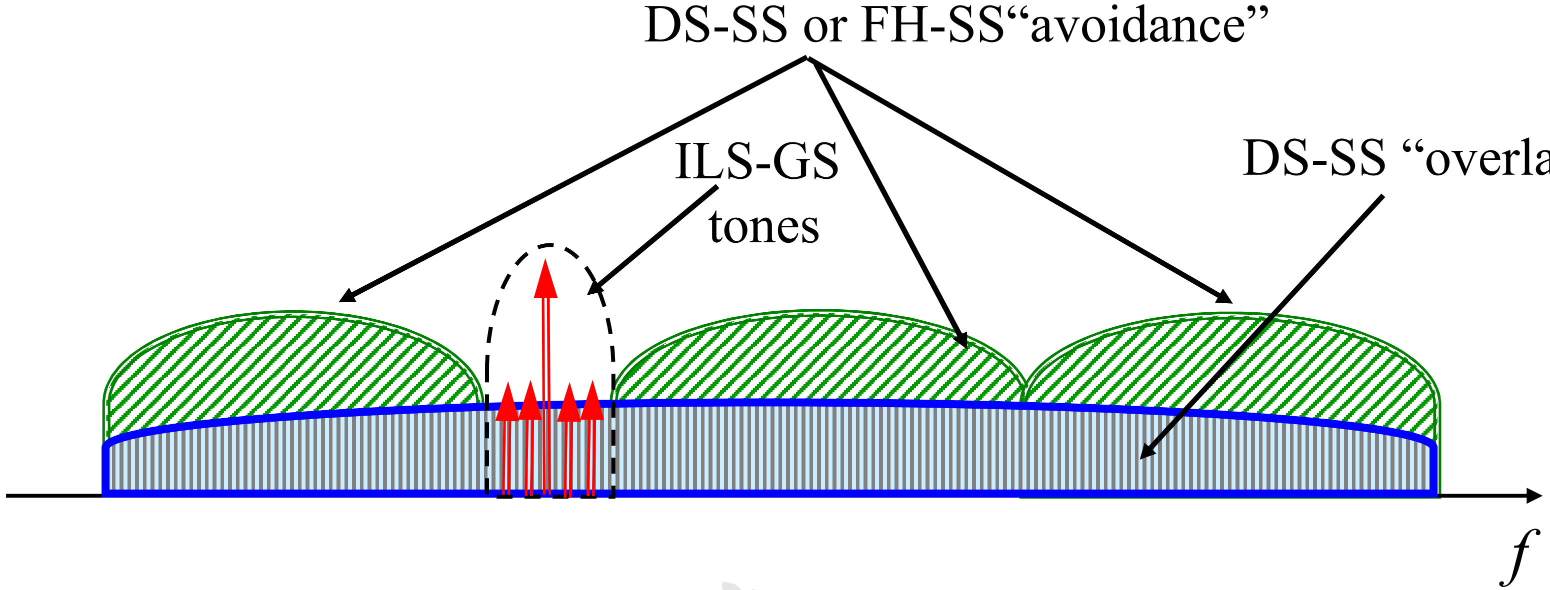
Parameter	MLS	ILS-GS	UAT	VDLM3
Frequency Band	5.0 – 5.25 GHz	329-335 MHz	960 – 1215 MHz	118-137 MHz
# Channels	200 in 5.031-5.0907 GHz + 198 more, up to 5.15 GHz	---	1	---
Approx Chan BW (90% P)	?	300 Hz	$1.4R_b$	$B_{90} \cong 16.8$ kHz
Multiple Access (MA)	NA	NA	TD (~S-ALOHA)	TDMA (polling & rand. acc.)
Channel R_b (kbps)	15.625	NA	1004.167	31.5
Minimum total frequency band for operation	~ 300 kHz?	300 Hz	~ 2 MHz (1 channel)	25 kHz
Duplex method	NA	NA	Time: dedicated uplink/downlink slots	Time: dedicated uplink/downlink slots
Minimum up/downlink Δf	Uplink transmission only	Uplink transmission only	0	0
Frequency planning requirements (re-use)	Since short range, full re-use possible; Δf spacing	Since short range, full re-use possible; Δf spacing	Unknown: likely re-use factor ≥ 7	Unknown: likely re-use factor ≥ 7
RF channel spacing Δf	300 kHz	?	~ 2 MHz	25 kHz
Spectral Eff. (bps/Hz)	≤ 1	NA	0.714	≅ 31.5/16.8 = 1.875
Max. User R_b (kbps) per timeslot	NA	NA	Air: 701.75; Ground: 921.51 (Counting user address as data)	19.2 (192 sym/30ms burst) (NOT counting address info)
Multi-User Capacity: contention effect on R_b	NA	NA	Degrade by 64% (multiply by 0.36) for MA (S-ALOHA)	With assigned channels, full R_b available
Modulation	DBPSK	DSB AM tone mod: two tones ±90, ±150 Hz from f_c	h=0.6, $\Delta f = hR_b$ = 625 kHz (900 kHz in practice)	D8PSK, with RRC pulse shaping, α = 0.6
Frame time	---	NA	1 second	120 ms
# Timeslots/frame	variable	NA	4000	3 or 4
Synchronization Seq.	12 bit preamble	NA	36 bit preamble	Two 16-symbol words/slot

Task 1 Results: ILS Glideslope Band

- 2 coexistence options w/tone-modulated ILS GS signal
  - Avoidance: utilize adjacent frequencies
    - Narrowband or Spread Spectrum (DS or FH)
  - Spectral Overlay
    - Direct-Sequence Spread Spectrum (DS-SS)
    - Power balancing between signals
    - Protect DS-SS via ILS-GS signal cancellation—easy for sinusoids
    - Protect GS via nulling transmitted DS-SS signal at GS frequencies
- Disadvantages to use of ILS-GS are
  - Limited bandwidth
  - For SS in overlay mode
    - Complexities (notch filters and/or interference cancellers) if ILS-GS sensitivity can not afford small degradation
  - For SS in avoidance mode
    - Very good filtering

Task 1: Two SS "Modes"

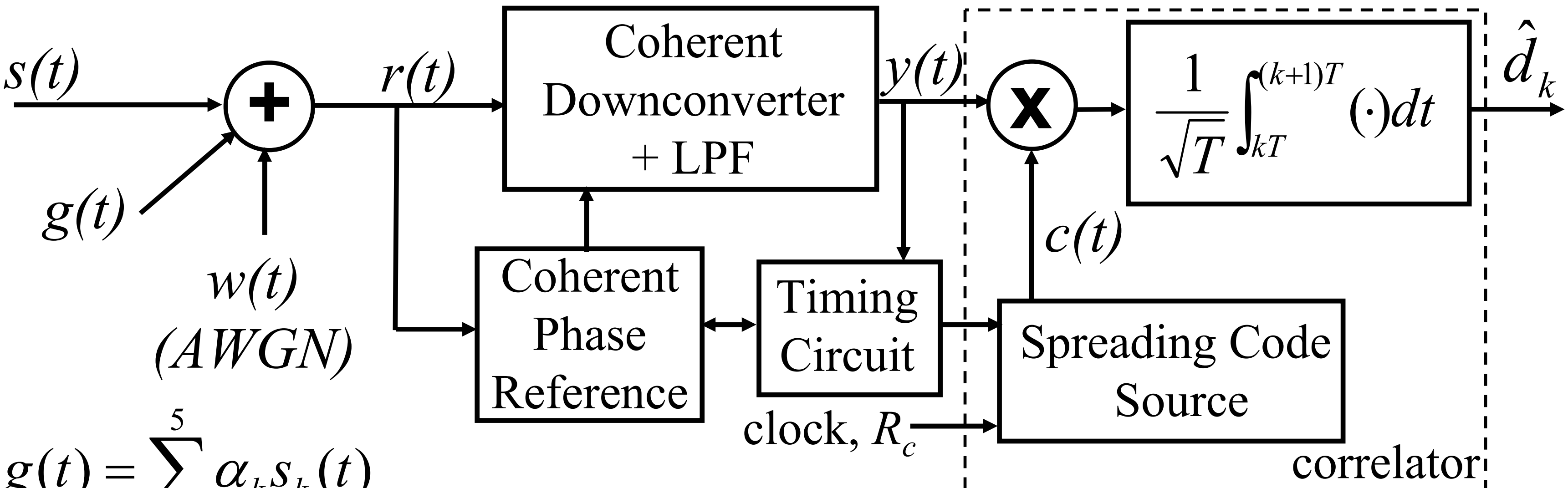
- Depiction of power spectra in two modes
  - Overlay
  - Avoidance
    - DS-SS (possibly multicarrier)
    - FH-SS



Model for Analysis: ILS-GS→DS-SS

BPSK DS-SS signal= $x_{DS,i}(t) = (A_i \cos\omega_c t)\sum_k \sum_{j=0}^{N-1} d_k^{(i)} c_{kN+j}^{(i)} p_{T_c}(t-(kN+j)T_c)$

ILS-GS signal=$g(t)$



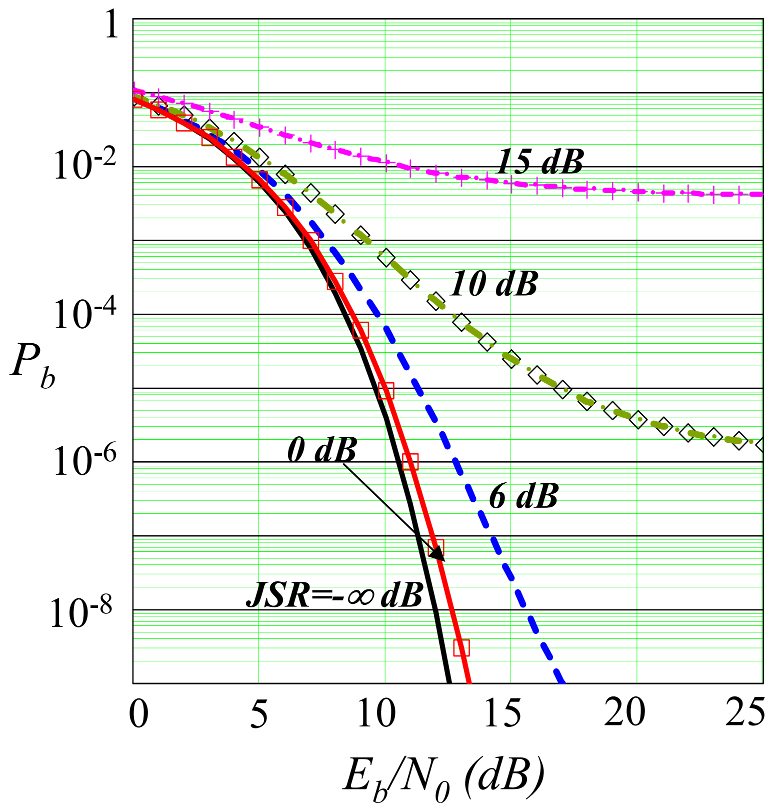
$$g(t) = \sum_{k=1}^{5} \alpha_k s_k(t)$$

$$s_k(t) = \cos(2\pi(f_c + f_k)t)$$

$$f_c \cong 330 \text{ MHz},\ f_k \in \{0, \pm 90, \pm 150\}$$

Effect of GS on DS-SS, Example 1

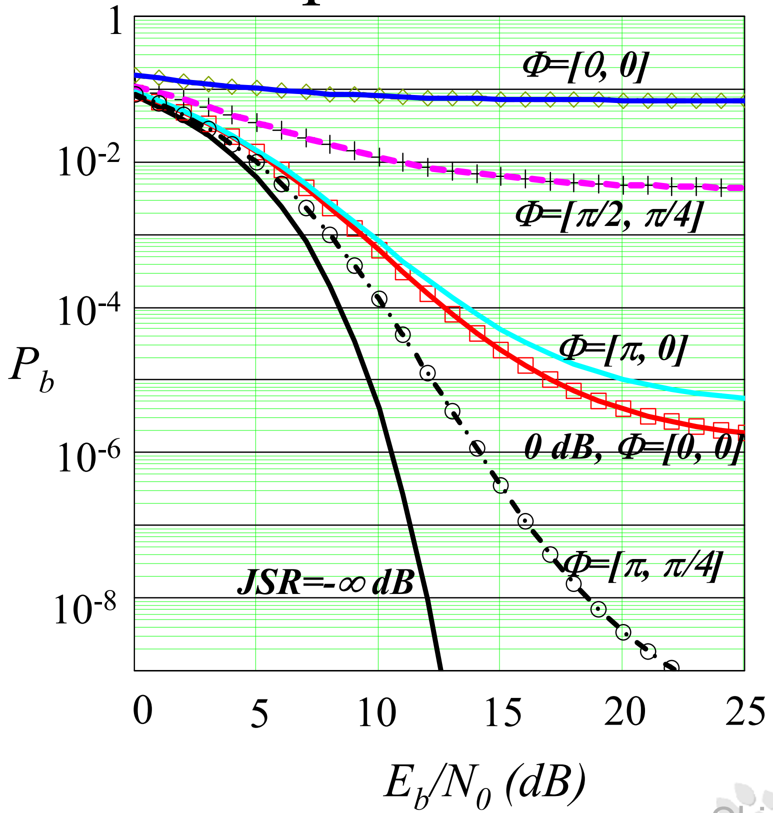
- DS-SS P_b vs. SNR, with $JSR=P_{GS}/P_{DS}$ a parameter



- DS-SS R_c = 5 MHz
- DS-SS R_b = **5 kbps**
- Equal center frequencies

Effect of GS on DS-SS, Example 2

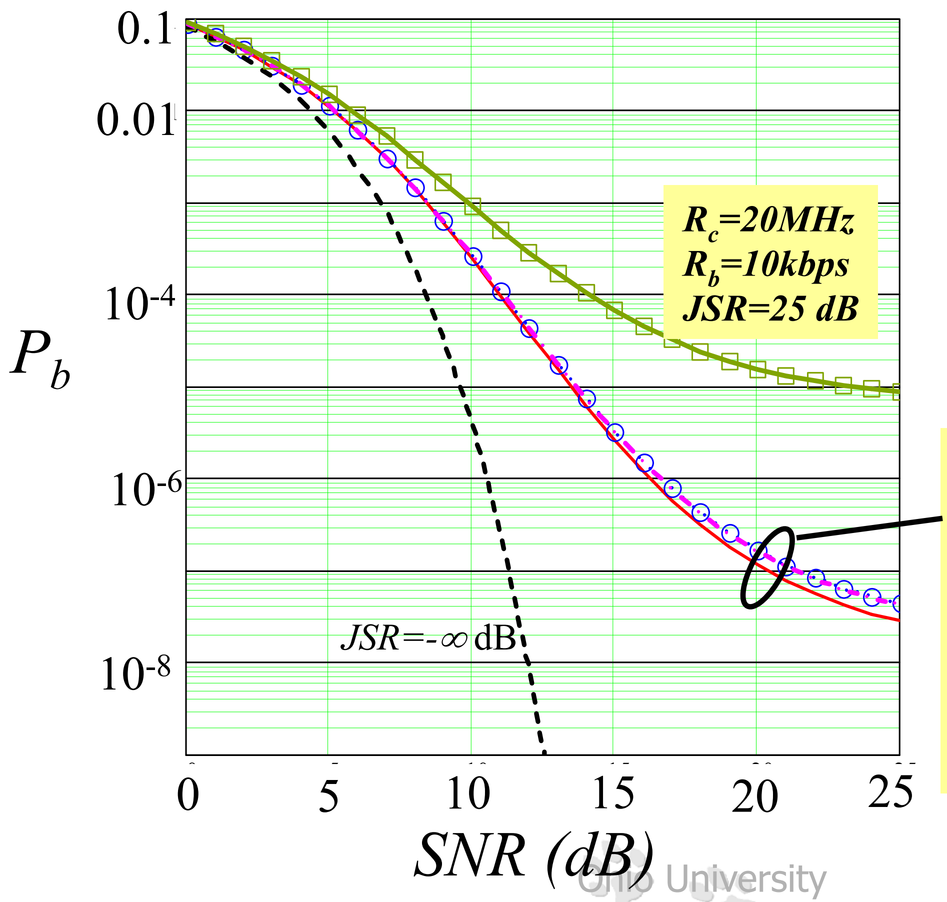
- DS-SS P_b vs. *SNR*, with $JSR=P_{GS}/P_{DS}$ & tone phases variable parameters



- DS-SS R_c = 5 MHz
- DS-SS R_b = **<u>50 kbps</u>**
- Equal center frequencies
- *JSR*=10 dB unless otherwise specified
- Smaller allowable *JSR* as DS-SS R_b increases

Task 1 Results: MLS effect on DS

- DS-SS P_b vs. *SNR*



- Parameters
  - $JSR = P_{MLS}/P_{DS}$
  - DS-SS R_c
  - DS-SS R_b